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Design for additive manufacturing and its effect on the performance characteristics of a control valve trim

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ABSTRACT

Additive Manufacturing methods have been gaining popularity over the traditional manufacturing methods in the past three decades due to shorter product development cycles and reduced manufacturing costs. Selective Laser Melting is one of the most popular methods of Additive Manufacturing. In this paper, the effect of the manufacturing method on the performance characteristics of disc stack trims manufactured by Selective Laser Melting is investigated. Initially manufactured trim showed a reduction in the flow capacity as compared to the trim manufactured by Electron Discharge Machining. The reason for the reduction in flow capacity was found to be the increased surface roughness of the trim manufactured by Selective Laser Melting. Therefore, changes were made to the process parameters within the manufacturing method to improve the surface finish and its corresponding effect on the valve trim's performance was assessed. Furthermore, a new design of the disc stack trim to aid the manufacturing method was also tested. The results showed that the changes to process parameters produced a negligible effect on the trim's performance but changes to the design of the valve trim resulted in improvement of the performance. Results thus indicate that for critical applications it may be necessary to alter the design of the components to derive most benefits from additive manufacturing technology.

Keywords: *Additive manufacturing; selective laser melting; control valves; disk stack trim; flow capacity.*

1. Introduction

In flow handling systems, control valves are used to provide accurate control of process parameters such as flow rate, pressure, temperature, etc. These valves can be quite complex, particularly in severe service applications. The process control is achieved by moving a plug against a seat inside a cage/stack. Thus, by varying the area available for the flow, the conditions of flow can be controlled. Stacks are composed of a number of stacked discs with complex fluid flow paths on their surface. Due to the nature of the flow paths on the discs, the pressure drop occurs in a number of stages, where at each stage, the flow area is expanded after each stage of pressure drop. Due to the expansion in the area, the fluid velocity across the surface of the disc is reduced in order to prevent problems like cavitation, erosion and noise. The design of severe service control valves has undergone significant changes over the past two decades from their original concept designs. Recent studies by Asim et al. [1, 2] have shown how the design changes can improve the performance of control valve trims with such complex flow paths by using Computational Fluid Dynamics based techniques. Currently, 90% of disc stack trims are manufactured using the Electron Discharge Machining (EDM) method, often known as Spark Eroding [3]. The remaining 10% are made using traditional machining operations such as milling, etc. The EDM method of manufacture can be quite costly for these trims with complex flow paths. Furthermore, EDM has relatively long lead times in the manufacturing process (of up to 10 weeks per disc stack), limiting the delivery times for original equipment [4].

In order to overcome the limitations of these manufacturing methods, Additive Manufacturing (AM) has gained a lot of popularity over the last three decades in order to facilitate shorter product development cycles, increasing demand for customised and personalised products, increased focus and regulations on sustainability and reduced manufacturing cost and lead times [5]. Laser Metal Deposition, Electron Beam Melting, Selective Laser Melting, Hybrid Laser Deposition Welding and Milling, and Metal Binder Jetting are some of the popular AM technologies [6, 7]. Out of these methods, Selective Laser Melting (SLM) offers significant advantages in printing complex parts with high density, improved mechanical properties and accuracy [7]. Originally, SLM was used for rapid prototyping and product development, however, in recent years, the development of newer and high-powered lasers has led to the use of SLM for more generalised production purposes. In the product development stage, products often require multiple changes, and using SLM, a number of designs can be manufactured at lower cost for performance evaluation.

SLM uses a laser beam to fuse very small particles of powdered material together which are held in a powder bed. Figure 1 shows a schematic of the basic components of a typical powder bed SLM machine. The process starts with depositing a layer of the powdered material in the powder bed. The laser selectively fuses the particles together from a cross section, provided directly from a 3D model of the part, on the surface of the powder bed. After each pass, the piston moves downwards and a wiper arm comes back across the powder bed which deposits the next layer of powder on to the powder bed. This process is repeated until the part is fully formed.

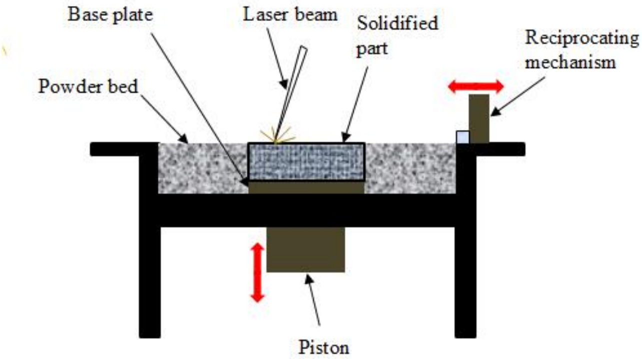


Figure 1. Basic components of a typical SLM machine

Tsopanos [8] states that the slicing operation is a critical stage in an SLM process. This operation generates the geometric description of each layer from the CAD representation which is used to define the part's cross-section for that layer. Tsopanos stated that for SLM manufactured parts, surface finish is a major concern and dedicated control systems need to be considered for the optimisation of this process. Surface finish is influenced by various manufacturing process parameters such as hatch spacing, build speed, laser power, laser spot size, powder layer thickness, point distance and exposure time. Hence, these parameters should be carefully selected in order to achieve required surface finish.

Enneti et al. [9] conducted experiments to investigate the effect of process parameters such as hatch spacing of 15 and 30 μm and build speeds in the range of 200-1400 mm/s. In these investigations, the authors used a constant laser power of 90 W and powder layer thickness of 30 μm on the densification of parts manufactured using tungsten. They found that the resulting density was inversely proportional to hatch spacing and build speed which means that smaller hatch spacing and slower scan speeds produce denser parts. Out of these two parameters, build speed was found to be the dominant factor. Hanzl et al. [10] found that build rate and laser power settings have the most significant effect on the mechanical and physical properties of the manufactured part. Their study also showed that the tensile properties of parts manufactured along the vertical axis were better than those manufactured along the horizontal axis. An angle of the building direction less than 45° resulted in deterioration of mechanical and geometrical properties due to the delamination of the layers.

Osakada and Shiomi [11] used Finite Element Analysis to investigate the deformation of SLM manufactured parts due to thermal distortion. They found that an increase in the length of scanning track caused the maximum tensile stresses to increase and thus, the amount of thermal distortion of a single layer increased. They suggested that the forming area should be divided into small segments when a large layer is formed on the powder bed.

Residual stresses may be induced during the SLM process due to the rapid heating and cooling during forming. Figure 2 shows a valve trim sample produced by SLM that suffered from such a deformity as a result of high residual stress, whereby the product is not flat on its top surface, nor is it round [3]. As can be seen from the figure, there is further material slippage on the side of the stack. Osakada and Shiomi [11] discovered that residual tensile stresses have a large effect on the deformities. They also found that large residual tensile stresses occur in the top layers of the model, and these stresses decrease rapidly with the distance from the top surface of the model. During the manufacturing process, residual stresses can be reduced by re-scanning during each layer formation, which provides more optimised control of the heat being applied to the component, thus reducing the speed of manufacture and prevent rapid heating. Build speed is, therefore, a very important parameter that needs to be considered when manufacturing parts, especially when approaching greater heights from the base plate.

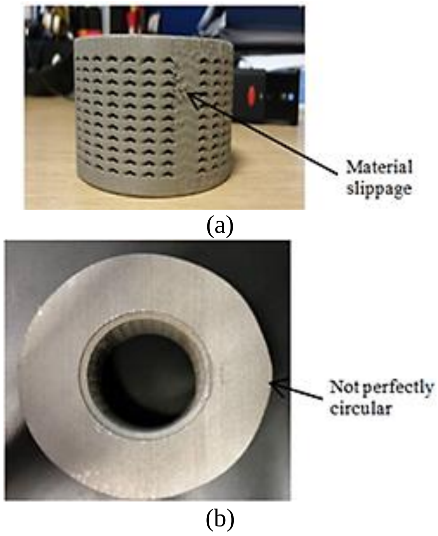


Figure 2. Material slippage and deformation on a SLM manufactured valve trim (a) Side view (b) Top view

Yadroitsev et al. [12] investigated the effect of the hatch distance over a range from 60 -140 μm on the porosity of the samples. For a laser spot size of 70 μm, power of 50 W, speed of 0.13 m/s and layer thickness of 50 μm, the individual vector width is 120 μm which is larger than the spot size of the laser. Thus, when the laser passes over again, there is a partial re-melting of the same vector, and this causes breaks in the layers, which eventually results in a defective porous structure. Yadroitsev et al. recommend using a technique called 'Two-Zones technique', for improving the porosity for an optimal hatch distance (around 120 μm). Using this process, where each layer of the powder was melted twice, the porosity was reduced to approximately 1%. This technique has been employed in the present study and the trims manufactured showed very low porosity as can be seen in the results and discussion section later.

Most of the literature published on SLM manufacturing is regarding manufacturing relatively simple parts, including some complex geometrical features. However, these parts are mostly open form (non-closed parts) where each surface is visible. The surface features of these parts can be fully reviewed post-manufacturing where they can undergo a finishing process. Complexity of equipment used in the flow handling industry can be very high. Therefore, this method is not suitable for manufacturing geometrically complex valve trims due to the closed nature of their design. For the wider acceptability of SLM method for manufacturing flow handling equipment, a thorough investigation is required.

The main focus of the present study is to critically evaluate the performance characteristics of the different valve trim designs which have been manufactured by the SLM process and compare their performances to the trim manufactured using the EDM method. It is also proposed to explore the relevant design changes as well as processes to mitigate performance issues when using additive manufacturing. Tests were initially conducted on the SLM trims manufactured in the study by Asim [13]. The SLM process parameters were then altered to improve the surface finish of the trim and the effect of the change in process parameters on the performance characteristics was investigated. A new design of the valve trim to aid the manufacturing method was created and its performance characteristics are also evaluated and compared against the original trim.

2. Flow capacity of control valve trim

One of the most important parameters that characterises the hydraulic performance of a valve is its flow coefficient, Cv. It is a function of the volumetric flow rate and the pressure drop across the valve, which are influenced by the surface finish of the valve. The trims manufactured by different manufacturing methods can result in different surface finishes and thus, their Cv values would be different. Cv is related to the volumetric flow rate and the pressure drop across the valve by equation (1):

$$Q = N_1 F_R F_P Cv_{total}\sqrt{\frac{\Delta p}{\frac{\rho}{\rho_o}}} \tag{1}$$

where Q is the volumetric flow rate, N_1 is a numerical constant that depends on the units used, F_r is the Reynolds number factor, F_p is the piping geometry factor, Cv_{Total} is the valve flow coefficient in US gallons min^{-1} $psi^{-1/2}$, Δp is the pressure drop across the valve and ρ/ρ_o is the relative density. If the units used for volumetric flow rate and differential pressure are m^3/h and kPa respectively, the value of N_1 is 0.0865. It was observed while conducting the experiments that flow rates were not small enough for non-turbulent flow. For turbulent flows, F_r = 1. With no fittings attached to the piping (such as expander, reducer etc.), F_p = 1. For water, ρ/ρ_o = 1. Thus, equation (1) can be written as:

$$Cv_{total} = \frac{Q}{0.0865}\sqrt{\frac{1}{\Delta p}} \tag{2}$$

The overall Cv of the control valve can be obtained using equation (2). The valve is composed of the the trim valve body and the seat, therefore, Cv_{Total} is the resultant of the Cv values of the trim, the valve body and the seat as shown in equation (3) [12]:

$$Cv_{total} = \frac{1}{\sqrt{\left(\frac{1}{Cv_{Trim}{}^2}\right)+\left(\frac{1}{Cv_{Valve\ Body}{}^2}\right)+\left(\frac{1}{Cv_{Seat}{}^2}\right)}} \tag{3}$$

Here, the values of Cv for the valve body and the seat are 301.6 and 65 respectively [12]. Therefore, to determine the Cv value for the trim, equation (3) can be transformed into:

$$Cv_{Trim} = \frac{1}{\sqrt{\left(\frac{1}{Cv_{total}{}^2}\right)-\left(\frac{1}{Cv_{Valve\ Body}{}^2}\right)-\left(\frac{1}{Cv_{Seat}{}^2}\right)}} \tag{4}$$

Cv_{Trim} (defined as per the process requirement) can then be related to geometry resulting in design of the trim. The values of flow capacities of the valve body and the seat are known, and thus only Cv_{Total} needs to be determined in order to calculate Cv_{Trim}. Therefore, it was necessary to conduct experiments in order to determine Cv_{Total} to compare the performance of various trims manufactured using the methods of EDM and SLM.

3. Experimental setup

For testing the capacity of the manufactured valve trims, experiments were conducted using a 100 mm control valve and water as the working fluid, using the flow loop set-up in general accordance with BS EN 60534-2-3 [14], and as per test procedure VT-QC-SP503 [13]. The test setup consisted of two straight lengths of pipe, connected at either ends of the valve, as shown in figure 3. The upstream pipe is 20 times longer than the nominal diameter of the pipe while the downstream pipe is 7 times longer than the nominal diameter of the pipe. There are no bends within eighteen pipe diameters (18d) downstream of the test valve. All entry points into the pipework are a minimum of 3 mm in diameter. Pressure taps are installed at a distance of two pipe diameters (2d) upstream of the valve and six pipe diameters (6d) downstream of the valve. Clean water is circulated through the flow loop via a centrifugal pump. The pump is controlled via an electrical invertor that can adjust the motor speed within 0.1% of the total 50 Hz output frequency.

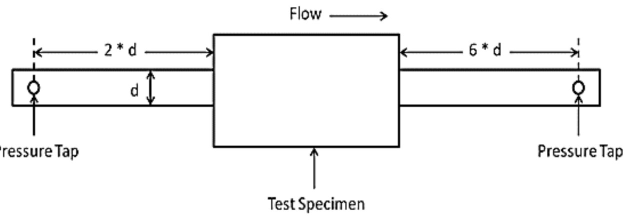


Figure 3. Schematic of the test section and position of pressure taps

A turbine flow meter is installed downstream of the pump, and upstream of the test valve, to monitor flow rate. A pressure transducer is connected to the upstream pressure taps to monitor gauge inlet pressure, and a differential pressure transducer is installed between the upstream and downstream taps to monitor the gauge differential pressure. The turbine flow meter and the pressure transducers are connected to the flow loop software via an Omega USB-4718 data acquisition module. A thermocouple is located within the water storage tank to measure the temperature of the test fluid. It is positioned to have a negligible effect on flow and pressure.

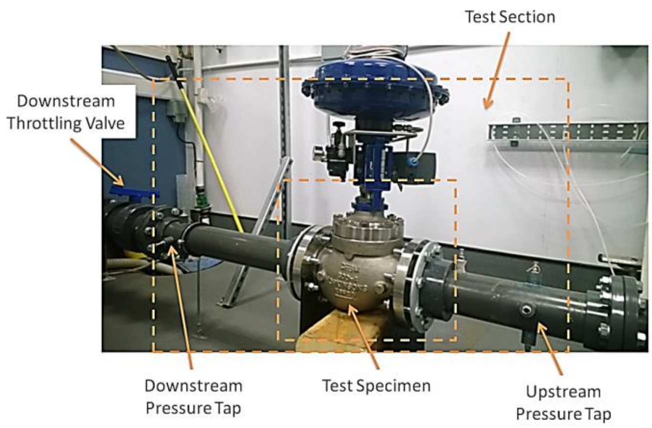


Figure 4. Flow loop set-up

Figure 4 shows a typical flow loop setup installed for the capacity testing of the control valves. The actuator, sitting on the top of the valve, is connected to an air supply at 4 bar,g, which controls the Valve Opening Position (VOP). It can be seen that four equally spaced pressure taps have been installed circumferentially at both upstream and downstream locations. These pressure taps measure the average pressure at the specified location, and hence, the three dimensional effects can be recorded more accurately.

Tests were performed at various flow rates resulting from different flow rates corresponding to the normal operating range of valve. At each flow rate, test data was recorded for various valve opening positions. The following data was recorded during the tests: VOP, inlet absolute pressure, pressure differential across the upstream and downstream pressure taps, inlet water temperature, volumetric flow rate and barometric pressure. The accuracy of the pressure sensors was ±0.25% FS and the flow rate sensor had an accuracy of ±3% FS. At each measurement condition, each measurement was recorded five times and it was averaged, therefore, the results reported in the results section are the averaged results. At each measurement condition, the standard deviations of the five repeated measurements of pressures and flow rates were within 2.7% and 9.4% of the mean values respectively.

4. Details of SLM manufacturing process employed and its effect on valve performance

4.1. Manufacturing process parameters for SLM

The trims manufactured using the EDM method and the SLM method are shown in figures 5(a) and 5(b). Figure 5(c) shows the geometry of a single disc of these trims. The trim manufactured by EDM was made up of 12 such discs while the SLM manufactured trim consisted of 11 discs, however, the difference in the number of discs has been eliminated in the analysis as will be seen section 4.2. Each disc has five rows of cylinders of various diameters. The diameters of these cylinders get smaller going from the outer diameter to the inner diameter. The flow direction is from the outer diameter of the discs to the inner diameter of the trim as shown in figure 5(c). The SLM trim was manufactured using a Renishaw AM250 machine and the process parameters for the SLM manufactured trim are shown in table 1. It can be seen from the table that the trim was manufactured in 16 hours which is significantly less time as compared to trims manufactured by EDM which takes approximately 3 weeks to complete. Enneti et al. [9] suggested that using a smaller hatch spacing results in a part with higher density. The hatch spacing used for manufacturing the trims by SLM was 13 μm which is close to the lower values of the hatch spacing used in their tests. Feature size is defined as the smallest geometric feature that can be produced by the SLM machine and thus is a measure of the accuracy of the process. The minimum feature size that can be produced by the SLM machine is double the laser spot size as a single feature requires a minimum of two spots to melt the powder to form the feature. Using the manufacturing parameters resulted in a high density part (99.80%) which is important because the strength of the part depends on the density of the part and its porosity. Density is reported in percentage here because it the relative density of the generated part to the particle density of the material.

The SLM trim was manufactured with an inner and an outer sleeve, as shown in figure 6, in order to reduce the deformities produced by thermal distortion and residual stresses by adding additional strength to the part during the printing phase, which would then need to be removed during the finishing phase. It can also be seen in figure 6 that these parts were manufactured through printing the stack at angles. Without this method, previous build attempts had failed to construct the part as the deformities were so large that the laser was unable to continue the printing phase.

4.2. Trim flow capacity comparison

Figure 7 shows the variation of Cv_{Trim} with flow rate at various valve opening positions for the EDM trim. The results show that as the valve opening position decreases, flow rate also decreases due to the decrease in the area available to flow. Due to the restriction in flow with decrease in valve opening position, pressure drop across the test section increases. At 100% valve opening position (VOP) and a maximum available volumetric flow rate (at maximum pump speed) of 51.8 m^3/hr, the pressure drop was 342.84 kPa. This gives a Cv_{Total} value of 32.3 and a Cv_{Trim} value of 37.5. It can be seen that by decreasing the VOP, the Cv values change drastically and at 10% VOP, the Cv shows an eightfold decrease approximately. At 100% VOP and a volumetric flow rate of 26.8 m^3/hr, the pressure drop was 90.96 kPa. This shows that by reducing the flow rate to half of the maximum available flow rate, the pressure drop decreases to 1/4 approximately. The corresponding Cv_{Total} values of 32.5 and a Cv_{Trim} value of 37.7 are similar to the maximum available flow rate of 51.8 m^3/hr. Similar trends can be seen for other VOPs at different flow rates. At 100% VOP and a volumetric flow rate of 15 m^3/hr and the pressure drop was 27 kPa and the corresponding Cv_{Total} and Cv_{Trim} values were 33.4 and 39.3 respectively. This shows that as the volumetric flow rate decreases to about ¼ of the maximum available flow rate, the pressure drop decreases to about 1/16. The Cv values are similar at all the flow rates at the same VOP.

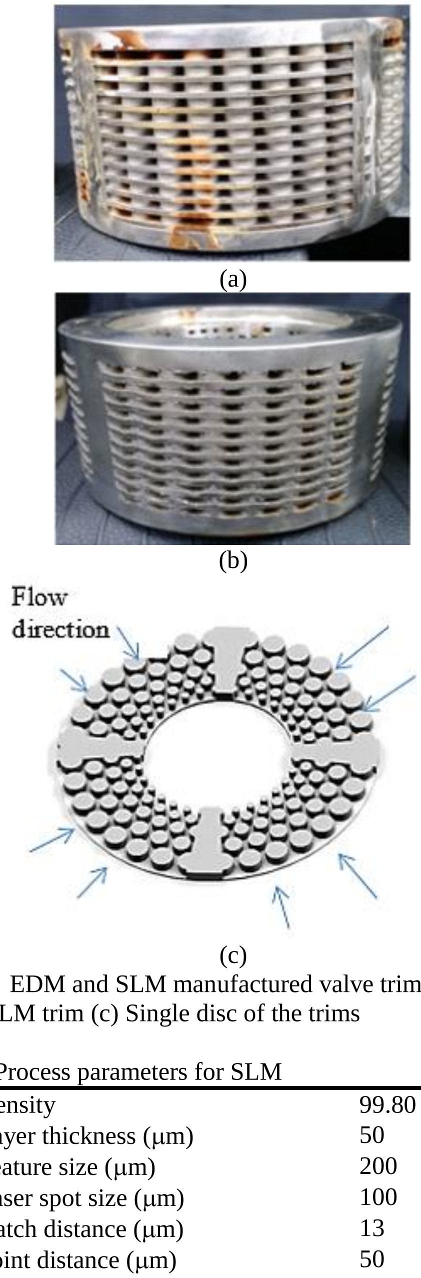


Figure 5. EDM and SLM manufactured valve trims (a) EDM trim (b) SLM trim (c) Single disc of the trims

Table 1. Process parameters for SLM

Density	99.80 %
Layer thickness (μm)	50
Feature size (μm)	200
Laser spot size (μm)	100
Hatch distance (μm)	13
Point distance (μm)	50
Laser power (W)	120
Exposure time (μs)	220
Overall production time (hours)	16

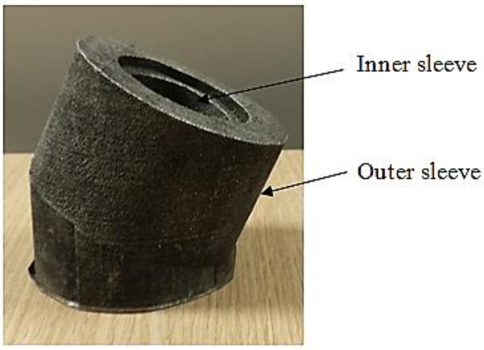


Figure 6. Trim manufactured with inner and outer sleeves and at an angle

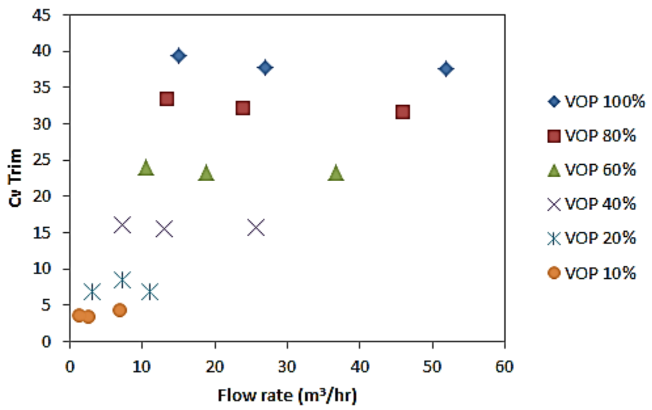


Figure 7. Variation of Cv_{Trim} with flow rate for various valve opening positions – EDM trim

It can be seen from figure 7 that Cv_{Trim} remains nearly constant for each valve opening position. It is expected because Cv_{Trim} is a function of valve opening position, and it is independent of flow conditions. At each VOP, three points are shown on the graph. Starting from the left, the first point corresponds to the Cv_{Trim} value at 25% pump speed, the second point corresponds to the Cv_{Trim} value at 50% pump speed and the third point corresponds to the Cv_{Trim} value at 100% pump speed. It can be seen from figure 7 that at each pump speed, Cv_{Trim} varies linearly with flow rate. It can also be seen that as the pump speed increases, the gradient of the Cv_{Trim} vs flow rate line decreases.

Figure 8 shows the variation of Cv_{Trim} with flow rate at various valve opening positions for the SLM trim. As can be seen from the figure, the results for this trim also shows similar trends in the variation of volumetric flow rate, pressure drop and Cv values as the EDM trim. At the maximum available flow rate and 100% VOP, the Cv_{Total} value is 24.5 and the Cv_{Trim} value is 26.6 for the full column SLM trim whereas, for the half column SLM trim, Cv_{Total} value is 22 and the Cv_{Trim} value is 23.4. Therefore, the full column SLM trim is capable of delivering higher Cv than the half column SLM trim. However, both of the trims manufactured by the SLM method exhibited lower Cv values than the trim manufactured by using the EDM method.

One reason for the decrease in performance of the trim manufactured by SLM is that the EDM trim had 12 discs whereas the SLM trims had 11 discs. In order to compare the performance with an EDM trim of 11 discs, the Cv_{Trim} values of the EDM trim have been adjusted in table 2 by finding the Cv for a single disc (dividing it by 12) and then multiplying by 11. The table shows the average values of Cv_{Trim} at each VOP for each of the trims. It can be seen that the Cv_{Trim} values for EDM trim were higher than the SLM trim. Thus, for a like-for-like number of discs, at 100% VOP, SLM trim has a reduction in capacity of 22.6%.

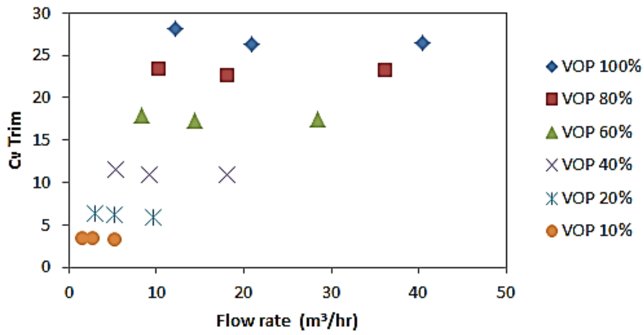


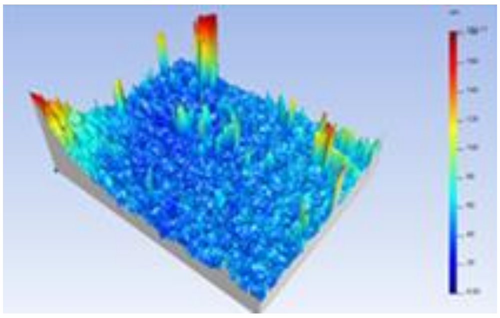
Figure 8. Variation of Cv_{Trim} with flow rate for various valve opening positions – SLM trim

Table 2. Average Cv_{Trim} at different valve opening positions

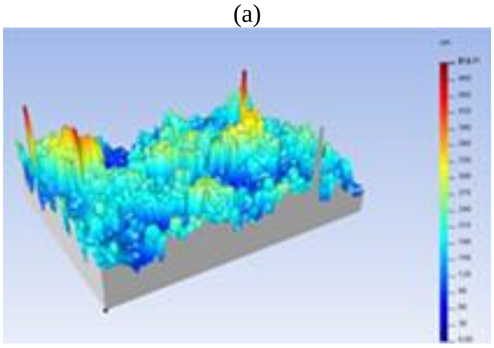
VOP (%)	EDM	EDM adjusted (11 discs)	SLM
100	38.17	34.99	27.07
80	32.17	29.49	23.00
60	23.57	21.61	17.60
40	15.83	14.51	11.10
20	7.33	6.72	6.10
10	3.57	3.27	3.27

Another reason for the reduction in the capacity is the likely difference in surface finish of these parts which is a direct outcome of manufacturing process parameters. It is visible from figure 5 that the EDM manufactured trim has a better surface finish than the SLM manufactured trim. In order to compare the surface finish of these parts, 3D surface roughness measurements were carried out at various sections of the trims using Talysurf CCI (Taylor Hobson). Figure 9 shows the surface topography of EDM and SLM trims. It can be seen from the figure that the surface finish of the EDM trim is highly non-uniform and dominated by large peaks. In case of the SLM trim, the surface finish is not only characterised by large peaks, but the core region of the surface is considerably rougher as compared to the EDM trim. The results depict that the roughness amplitude in SLM trims can be as high as 500 microns while for the EDM trim, it is about 200 microns. Thus, the higher surface roughness on the SLM trims may be a major factor in the reduction of the capacity of theses trims as it offers an increased resistance to the flow [15]. This argument is further strengthened by the fact that the Sdr parameter of SLM surfaces was significantly higher than EDM trims. Sdr parameter is the developed interfacial area ratio, which shows the percentage increase of the area of the actual surface compared to the planar surface area [16]. The average Sdr parameter for the EDM trim was 82.36% whereas for the SLM trim, it was 229.08% which is significantly higher. This means that for the SLM trims, the surface area in contact with the fluid is higher which results in greater resistance to the flow, and hence, a reduction in Cv.

Valve capacity is one of the most important factors to be considered in valve design by the valve companies, as this can result in a competitive price advantage over their competitors. The SLM method showed a 50% reduction in costs of manufacture and significant reduction in manufacturing lead times, but when comparing like-for-like sizes against EDM, the significant reduction in Cv means that this cost advantage could be offset by the reduction in flow capacity through the valve. Thus, attempts were made to improve the capacity of the trims by altering the process of manufacture, or by making changes to the design.



(a)



(b)

Figure 9. Surface peak analysis (a) EDM trim (b) SLM trim

5. Improvements in process parameters and design

In the parts manufactured previously, the removal of the inner sleeve and the outer sleeve may also have an effect on fluid flow, because removal using a standard turning machining operation leaves flashing/burring of the metal, which requires significant de-burring operations. The deformities were still evident in the trim after the removal of these features. During the machining phase, it was found that the sleeves did not appear to be of a constant thickness, around the circumference of the stack. Therefore, improvements were made to the process parameters to manufacture the trims without the sleeves and to improve the surface finish. Furthermore, a new trim design was created to aid the manufacturing method so that deformities could be reduced.

5.1. Trim 1: Improved process parameters

In order to determine the optimum process parameters (as mentioned in table 1) for manufacturing the first trim, various trials were completed on test block samples where variations could be made with regards to certain process parameters. The density of the part is quite important to ensure that the manufactured part meets the tensile and yield strength requirements as well as the hardness requirement so that it conforms to the material standards for resistance to erosion. Parts that are manufactured below the required strength (as a result of poor density) could be prone to premature wear/failure. Higher laser power enables the machine to produce parts much quicker (at higher build speed), however, density reduces with an increase in build speed as there is not enough time for the laser beam to penetrate the powder and melt it.

The features monitored during the block tests were the point distance and exposure time, and laser power was kept constant. figure 10 shows a series of test blocks that were manufactured during these trials, varying the exposure time from 50 μs to 300 μs and the point distance from 30 μm to 200 μm. It can be seen that a number of the blocks failed to form at all, which was a direct result of insufficient energy transferred to the powder; a direct result of poor exposure time, to fully melt the powder and form the part.

Figure 10. Manufactured test blocks during trials

Tables 3 and 4 shows the results of the blocks manufactured at different exposure times and point distances. Table 3 shows the number of builds that were successful. It can be seen from the table that exposure times of 100 μs and 150 μs resulted in most number of successful builds. Out of the 12 blocks manufactured at each exposure time, 8 blocks for an exposure time of 100 μs and 10 blocks for an exposure time of 150 μs were successfully built. No builds were successful at an exposure time of 50 μs. For 100 μs exposure time, both the blocks were successfully manufactured at point distances of 30 μm up to 132 μm whereas for an exposure time of 150 μs, both the blocks were successfully manufactured at point distances of 30 μm up to 166 μm. Furthermore, the wall thickness of the parts was also measured and compared for certain samples as shown in table 4. It can be seen that the most successful features (highest wall thickness) were produced when the point distance was at its lowest value of 30 μm and at an exposure time of 150 μs with a wall thickness of 0.38 mm. Thus, an exposure time of 150 μs and a point distance of 30 μm were chosen to manufacture the new trim.

Table 3. Number of blocks built successfully at different exposure times and point distances

Point distance	Exposure time (μs)					
(μm)	50	100	150	200	250	300
30	0	2	2	1	1	1
64	0	2	2	1	1	1
98	0	2	2	2	1	1
132	0	2	2	2	2	1
166	0	0	2	0	0	1
200	0	0	0	0	0	1

Table 4. Wall thickness of blocks manufactured at different exposure times and point distances

Point distance	Exposure time (μs)			
(μm)	100	150	200	250
30	0.34	0.38	0.26	0.27
64	0.28	0.31	0.24	0.28
98	0.29	0.3	0.24	0.29
132	0.26	0.29	0.29	0.29
166	-	0.23	-	-
200	-	-	-	-

5.2. Trim 2: New design

In all the previously manufactured trims, the discs were flat which resulted in some unsupported areas, as shown in figure 11. These unsupported layers can get deformed during the manufacturing process [11]. This was one of the reasons for manufacturing the initial trims at an angle, however, printing the parts this way actually worsened the effect due to gravitational force tending to move the powder. Thus, a new design was considered for testing which consisted of arcs in between the cylinders to aid the manufacturing process as shown in figure 12.

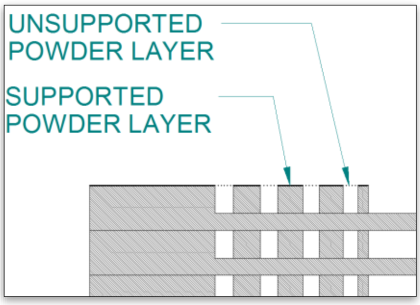


Figure 11. Supported and unsupported areas on the discs

A further design alteration includes the addition of a tear drop/aerofoil shape to the largest outer diameter column on the side linking to the outer edge of the trim. This feature was designed not only to increase the support to the layer above it, but also to assist the performance of the trim by potentially removing the sharp angle for entry of the process fluid to the trim. The aerofoil shape could also help in improving the overall surface finish of the trim by adding an extra feature at this area to improve the strength and reducing the residual stress and restricting deformation of the surface.

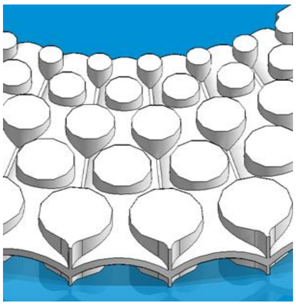
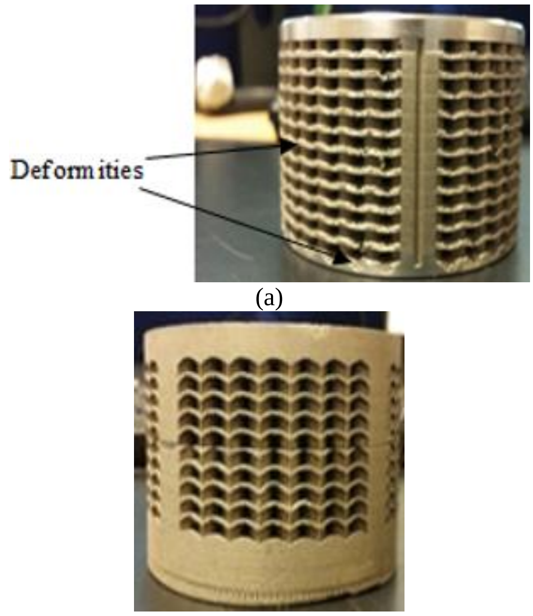


Figure 12. Single disc view for the new design

The idea of using aerofoils within the trim specifically at the entrance had been considered previously, however, this had never been successfully applied using the EDM manufacturing method, because it was not possible to create features of such a small size (less than 1.2 mm) accurately using the EDM method. However, as these restrictions were not the same with SLM, it was trialed with this concept. The process parameters were kept nearly the same as the original SLM trim except that the laser spot size was changed to 20 microns to form the features with higher accuracy and the exposure time was slightly reduced as well. The hatch distance was also much smaller for the new process parameters (10 mm for Trim 2 as compared to 80 mm for Trim 1) which meant that the part produced would be denser.

The two newly manufactured trims are shown in figure 13. It can be seen from the figure that the trim based on the new design exhibited lower surface deformities of the disc outer surface. The process parameters for manufacturing the new trims are shown in table 5. As can be seen from the results of build time, the new process parameters resulted in a significant increase in the production time, 35 hours compared to 14 hours for the new design trim. Both the parts showed high values for density, with the part produced using new process parameters having higher density by 0.1%, possibly as a result of the much smaller powder layer thickness. This low value for powder layer thickness is also the principal reason why the build rate was much slower as compared to the other builds as nearly double the number of layers were required.



(a)

(b)

Figure 13. New valve trims manufactured using SLM (a) Original design SLM trim-new process (b) New design SLM trim

Table 5. Process parameters used for manufacturing the trims

	Original SLM trim design – New process	New design SLM trim
Machine used	M1 Concept Laser 200W	Realiser SLM 100
Density	99.90 %	99.80 %
Layer thickness (µm)	30	50
Feature size (µm)	180	40
Laser spot size (µm)	90	20
Hatch distance (µm)	80	10
Point distance (µm)	30	50
Laser power (W)	200 & 90	120
Exposure time (µs)	150	200
Overall production time (hours)	35	14

6. Results and discussion

Figure 14 shows the variations in Cv_{Trim} at different flow rates for various valve opening positions for Trim 1. Similar to the previously manufactured trims, the results show that for each VOP, the Cv values remain constant irrespective of the flow rate. At 100% VOP and at the maximum flow rate of 38.4 m^3/hr, the pressure drop was 287 kPa. This gives a Cv_{Total} value of 26.2 and a Cv_{Trim} value of 28.7. It can be seen that by decreasing the VOP, the Cv values change drastically and at 25% VOP, the Cv values are reduced to 1/4 approximately. At 100% VOP and a volumetric flow rate of 19.3 m^3/hr, the pressure drop was 73 kPa. This shows that by reducing the volumetric flow rate by half, the pressure drop decreases to 1/4 approximately similar to the previously manufactured trims. The corresponding Cv_{Total} value of 26 and a Cv_{Trim} value of 28.5 are similar to the maximum flow rate. Similar trends can be seen for other VOPs at different flow rates. At 100% VOP and a volumetric flow rate of 6 m^3/hr, the pressure drop was 7 kPa and the corresponding Cv_{Total} and Cv_{Trim} values were 26 and 28.5 respectively. As the valve opening position increases, Cv_{Trim} increases. The increase in Cv_{Trim} with regards to the valve opening position is almost linear as expected. It can also be seen in the figure that for various flow conditions, Cv_{Trim} is nearly constant at a specific valve opening position. The original design trim, manufactured using the previous SLM process parameters, resulted in a Cv_{Trim} value of 26.6 for a VOP of 100%. The new trim with improved SLM process parameters shows an improved Cv_{Trim} of 28.7.

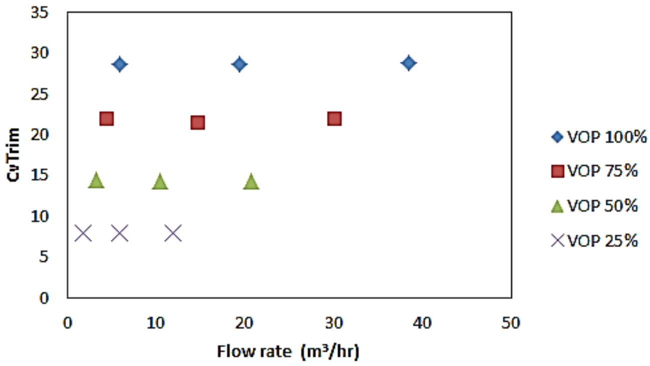


Figure 14. Variation of Cv_{Trim} with flow rate at various valve opening positions - Trim 1

Figure 15 shows the variations in Cv_{Trim} at different flow rates for various valve openings for Trim 2. At 100% VOP and a volumetric flow rate of 43.8 m^3/hr, the pressure drop was 287 kPa. This gives a Cv_{Total} value of 29.88 and a Cv_{Trim} value 33.85. It can be seen that by decreasing the VOP, the Cv values change drastically and at 25% VOP, the Cv values are reduced to 1/4 approximately, similar to Trim 1. At 100% VOP and a volumetric flow rate of 22 m^3/hr, the pressure drop was 73 kPa. Again, as the volumetric flow rate decreases by half, the pressure drop decreases to one-fourth approximately. The corresponding Cv_{Total} value of 29.81 and a Cv_{Trim} value of 33.75 are similar to the ones at the maximum flow rate. Similar trends can be seen for other VOPs at other flow rate conditions. At 100% VOP and a volumetric flow rate of 6.7 m^3/hr, the pressure drop was 6.7 kPa and the corresponding Cv_{Total} and Cv_{Trim} values were 29.84 and 33.8 respectively.

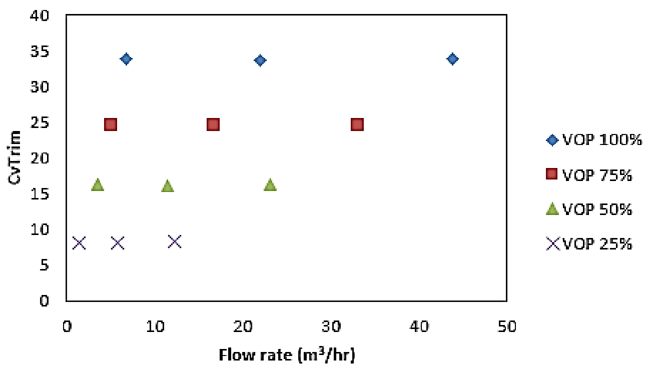


Figure 15. Variation of Cv_{Trim} with flow rate at various valve opening positions -Trim 2

Similar to the results for Trim 1, the trend is showing an almost linear trend of increase in Cv_{Trim} with respect to flow rate and VOP. Again, this effect is constant and independent of flow conditions. The Cv_{Trim} values of Trim 2 at 100% VOP are now higher than those for the original SLM trim and Trim 1 with an increase of 27.3% and 17.6% respectively. In comparison to the EDM trim, the difference in capacity is reduced to about 9.9%. Therefore, the difference in capacity of the new design SLM trim is now below 10% as compared to the original EDM trim while there is a cost reduction of about 50% and a significant reduction in the manufacturing time (hours instead of weeks). All of these factors combined make the SLM method of manufacture very promising for the production of these geometrically complex control valve trims.

7. Conclusions

The effects of manufacturing method of EDM and SLM on the performance characteristics of a complex control valve trim have been analysed in detail. It has been found that manufacturing the trims using the SLM method is cost effective but the trims manufactured initially showed some geometric imperfections and a significant reduction in the performance characteristics. Therefore, improvements were made to the method of manufacture and to the trim design to aid the manufacturing method. The results showed that changing the process parameters to improve the surface finish on the SLM trim showed a very small effect on the valve trim performance characteristics whereas changing the design to aid the manufacturing process resulted in an increase in the performance characteristics of the valve trim. Furthermore, the newly designed trim with new process parameters also takes less time to manufacture and thus, can decrease lead times for manufacturing and these can be manufactured at a significantly reduced cost than those manufactured using the EDM method. Design optimisation is not usually considered when making manufacturing process changes which may be useful to improve the performance of the part. The overall reduction in Cv_{Trim} against EDM part is now below 10% and combined with the cost saving potential, this makes SLM attractive for manufacturing geometrically complex trims.

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